

NLO QCD+EW automation and precise predictions for V+multijet production

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In this talk we present a fully automated implementation of next-to-leading order electroweak (NLO EW) corrections in OPENLOOPS together with SHERPA and MUNICH. As a first application, we present NLO QCD+EW predictions for the production of positively charged W bosons in association with up to three jets and for the production of a Z boson or photon in association with one jet.

1 Introduction

The upcoming Run-II of the LHC will probe the Standard Model (SM) of particle physics at unprecedented energies and precision. At the TeV energy scale higher-order electroweak (EW) corrections can be strongly enhanced due to the presence of large Sudakov logarithms. Their inclusion in the experimental analyses will significantly enhance the sensitivity for new phenomena. Here we present a fully automated implementation of next-to-leading order (NLO) EW corrections, applicable to any process within the SM.

In the following, first we briefly review the recently accomplished automation of NLO EW corrections in OPENLOOPS¹, SHERPA² and MUNICH³. Subsequently, we present numerical results for W +multijet production and for Z -boson and photon production in conjunction with one jet. Due to the large cross sections and clean experimental signatures these processes represent an ideal laboratory to test the validity of theoretical methods and tools that are used for the simulation of a vast range of processes at the LHC. Furthermore, they are important backgrounds for top- and Higgs-physics and various searches for physics beyond the Standard Model including Dark Matter searches in the monojet channel.

Discussion and results presented here are partly based on⁴, where more details can be found.

2 NLO QCD+EW automation in OpenLoops + Sherpa/Munich

The calculation of NLO QCD corrections for any SM process was already well established in the OPENLOOPS+SHERPA/MUNICH programs. This fully automated framework has now been extended to NLO EW calculations. More precisely, the new implementation allows for NLO calculations at any given Order $\alpha_s^n \alpha^m$, including all relevant QCD–EW interference effects. Full NLO SM calculations that include all possible $\mathcal{O}(\alpha_s^{n+k} \alpha^{m-k})$ contributions to a certain process are also supported.

The OPENLOOPS¹ program generates all relevant matrix-element ingredients, i.e. one-loop amplitudes, tree amplitudes for Born and bremsstrahlung contributions, as well as colour-

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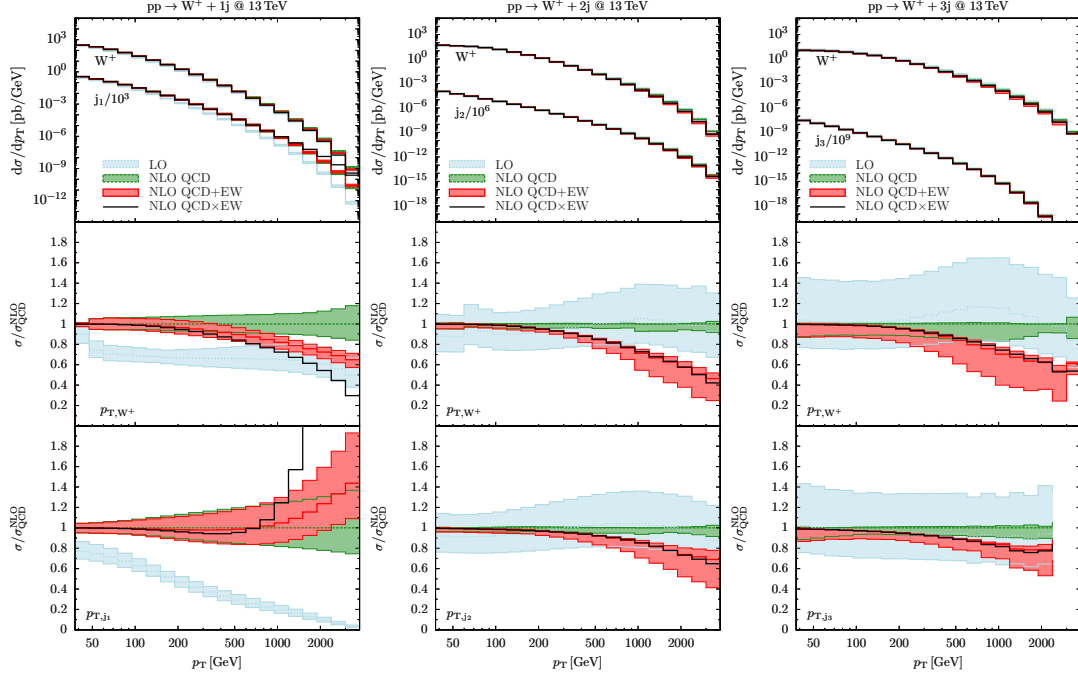


Figure 1 – Distributions in the transverse momentum p_T of the W^+ and the n -th jet for inclusive $W^+ + nj$ production with $n = 1$ (left), $n = 2$ (center), $n = 3$ (right) at $\sqrt{s} = 13$ TeV. Absolute LO (light blue), NLO QCD (green), NLO QCD+EW (red) and NLO QCD \times EW (black) predictions (upper panel) and relative corrections with respect to NLO QCD (lower panels). The bands correspond to scale variations, and in the case of relative corrections only the numerator is varied.

charge-, gluon-helicity and photon-helicity correlations that are needed for infrared subtractions. The OPENLOOPS program is based on the Open Loops algorithm⁵, which employs a recursion to construct loops as tree structures supplemented with full loop-momentum information. Combined with the COLLIER tensor reduction library⁶ the employed recursion permits to achieve very high CPU performance and a high degree of numerical stability.

The kernel of the Open Loops recursion is universal and depends only on the Lagrangian of the model at hand. The algorithm is thus applicable to any process within any renormalizable theory. The implementation has successfully been applied to various precision studies at NLO QCD and the extension to NLO electroweak corrections has very recently been achieved. It required the implementation of all $\mathcal{O}(\alpha)$ EW Feynman rules in the framework of the numerical Open Loops recursion including counterterms associated with so-called R_2 rational parts⁷ and with the on-shell renormalization of UV singularities⁸. Additionally for the treatment of heavy unstable particles the complex mass scheme has been implemented. For the convenience of the user the OPENLOOPS program is accompanied by a large process library including more than a hundred LHC processes – currently all at the NLO QCD level but the library will be extended to NLO EW soon.

All complementary tasks, i.e. the bookkeeping of partonic processes, the subtraction of IR singularities, and phase space integration, have been automated within MUNICH and SHERPA. Automated NLO EW simulations will be supported by future public releases of the employed tools.

3 W +multijet production

As a first highly non-trivial application we study the production of $W^+ + n$ jets with $n = 1, 2, 3$ at the LHC including NLO QCD and NLO EW corrections. In Fig. 1 we show differential distribution in the transverse momentum of the produced W^+ and the n -th jet. We use the

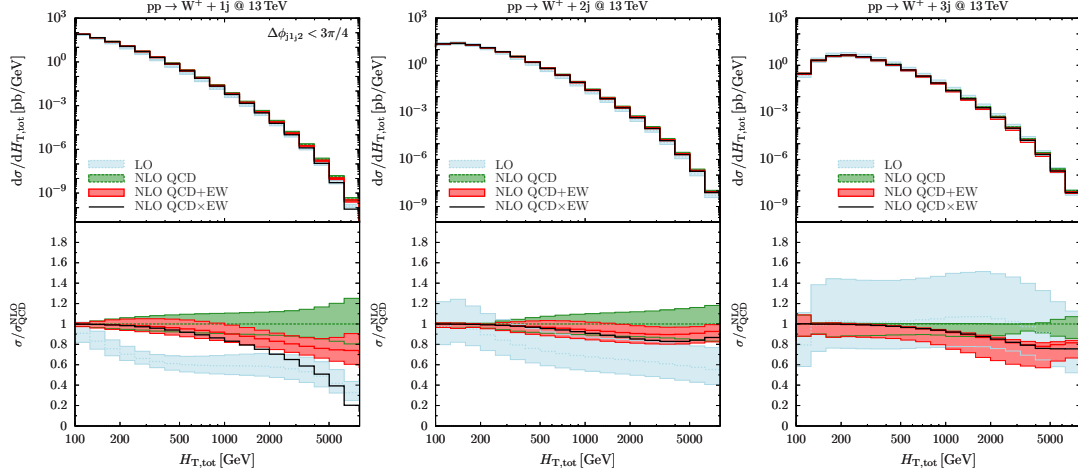


Figure 2 – Distributions in H_T^{tot} for exclusive $W^+ + 1j$ (left), inclusive $W^+ + 2j$ (center) and inclusive $W^+ + 3j$ (right) production. Curves and bands as in Fig. 1.

anti- k_T jet clustering algorithm with $R=0.4$ and require $p_T > 30$ GeV and $|\eta| < 4.5$ for the jets. Besides LO predictions of $\mathcal{O}(\alpha_S^n \alpha)$ we show NLO QCD predictions including corrections of $\mathcal{O}(\alpha_S^{n+1} \alpha)$ and NLO QCD + EW predictions including $\mathcal{O}(\alpha_S^{n+1} \alpha) + \mathcal{O}(\alpha_S^n \alpha^2)$ corrections. Theoretical uncertainties are assessed by standard variations of the renormalization and factorization scales.⁴ Besides QCD + EW predictions we also show factorized QCD \times EW predictions where the NLO QCD predictions are multiplied with a NLO EW K-factor. A difference between the two approaches indicates uncertainties due to missing two-loop EW-QCD corrections. In the lower panel we show corrections with respect to the NLO QCD prediction. In the tail of the p_T distribution of the jet in $W + 1$ jet production the NLO QCD corrections grow larger than a factor of 10 and the EW corrections turn positive. Together with the large scale uncertainties this is a clear indication for a poor perturbative convergence. Indeed, NLO corrections to inclusive $W + 1$ jet production are dominated by dijet configurations radiating a relatively soft W , which are effectively of leading order. Such configurations appear already at LO for $W + 2$ jet production (shown in the central plot), where the NLO QCD corrections are small and stable. Here, the EW corrections show a typical Sudakov behaviour and reach $-30(-60)\%$ and $-15(-25)\%$ at 1(4) TeV for the p_T of the W^+ and the 2nd jet respectively. A similar picture emerges for $W + 3$ jet production (shown in the right plot).

In Fig. 2 we show differential distributions in H_T^{tot} – the scalar sum of all final state transverse momenta for $W^+ + 1, 2, 3j$ production. In order to improve the perturbative convergence in the case of $W^+ + 1j$ production we employ a veto on a second jet if $\Delta\phi_{j_1 j_2} > 3/4\pi$. Still, for very large H_T^{tot} the QCD corrections to $W^+ + 1j$ and $W^+ + 2j$ production increase strongly, suppressing the impact of the EW corrections. Only for $W^+ + 3j$ production the QCD corrections are stable in all of the considered range. However, here the EW corrections are still moderate and only increase beyond the NLO QCD scale uncertainties for H_T^{tot} at the TeV scale.

4 Z/γ +jet production

As a second application we study the production of a Z boson or a photon in association with a jet at the LHC with $\sqrt{s} = 8$ TeV. The ratio of these processes differential in the p_T of the produced gauge bosons can be used to model $Z(\rightarrow \nu\bar{\nu}) + 1j$ production from a precise experimental measurement of $\gamma + 1j$ production, i.e. the dominant irreducible SM background in monojet searches for Dark Matter.

Results in the p_T of the produced weak gauge boson are shown in Fig. 3 with the same color coding and nomenclature as before. In the left and central plot results for $Z + 1j$ and

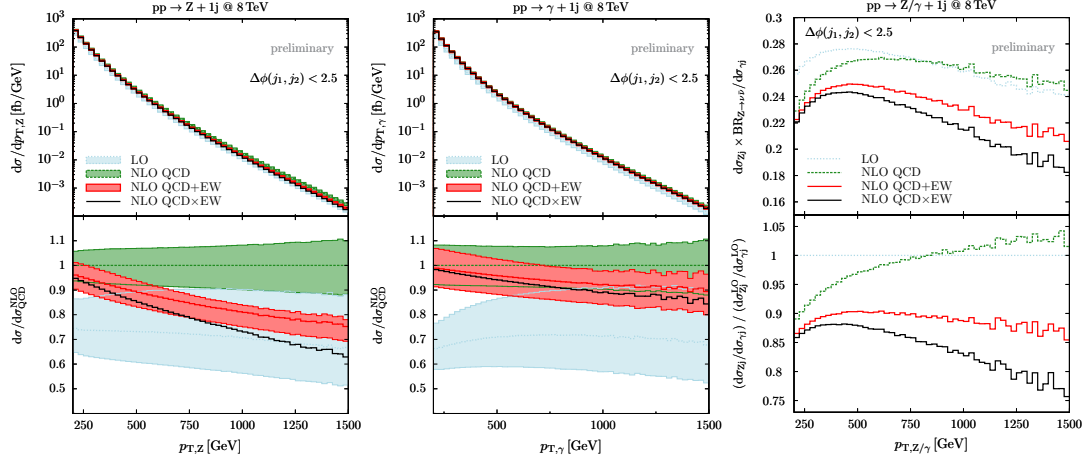


Figure 3 – Distributions in the transverse momenta of the Z boson (left) and of the photon (center) for $Z + 1j$ and $\gamma + 1j$ production at $\sqrt{s} = 8$ TeV. Curves and bands as in Fig. 1. In the right plot the ratio of the p_T of the Z and the photon together with the relative corrections in the ratio with respect to the LO ratio are shown using the same color coding as before.

$\gamma + 1j$ production are shown respectively. We require for the associated jet $p_{T,j} > 110$ GeV and $|\eta_j| < 2.4$ and veto a possible second jet with $p_{T,j} > 30$ GeV and $\Delta\phi_{j1j2} > 2.5$. These cuts are in agreement with a setup employed by CMS in an upcoming monojet search. The NLO QCD corrections to both processes are almost identical at large transverse momentum of the produced gauge bosons $p_{T,V}$, while they differ slightly at small $p_{T,V}$ due to the finite mass of the produced Z . NLO QCD scale uncertainties are at the level of 10%. On the contrary, the EW corrections to $Z + 1j$ production are enhanced compared to $\gamma + 1j$ production and at 1 TeV they reach -20% and -8% respectively. In the right plot of Fig. 3 we show the ratio in $p_{T,V}$ of $Z + 1j$ over $\gamma + 1j$ production. This observable is fairly stable in the considered p_T range and QCD corrections are below 10%. However, EW corrections result in an almost constant shift of about 10% comparing the p_T -ratio at LO and NLO QCD + EW. Such a shift is consistent with the observed deviation presented by CMS at Moriond 2015 QCD (also shown in Fig. 6 of⁹).

5 Conclusions

Recent progress in the automation of perturbative calculations within the OPENLOOPS +MUNICH/SHERPA frameworks has opened the door to NLO QCD+EW simulations for a vast range of Standard Model processes, up to high particle multiplicity, at current and future colliders. The large impact of NLO EW effects in V +multijet production at high energy demonstrates the relevance of these new tools for the upcoming Run-II of the LHC.

References

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